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A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction

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ABSTRACT

Excessive greenhouse gas (GHG) emissions have caused serious global warming and climate change. As the construction and demolition waste (CDW) end of life disposal process is a source of GHG emissions, it is vital to precisely estimate and reduce CDW end of life GHG emissions. The precise estimation of CDW information is essential for GHG estimation and reduction. However, as current CDW information and associated GHG estimation methods tend to be inaccurate, in this paper, a building information modeling (BIM)-based CDW information management system (IMS) is constructed that provides precise CDW information and a detailed information estimation process. To facilitate the accurate quantification of CDW disposal GHG emissions, mathematical formulae that include several GHG emission factors are proposed. A practical case study from China is then given to demonstrate the efficiency and effectiveness of the proposed methodology in quantifying and reducing CDW disposal GHG emissions. Accurate GHG emission estimation are determined for fifteen CDW disposal types and a comparison are conducted. Concrete was found to have the highest carbon dioxide, methane, and nitrous oxide emissions during transportation and the highest carbon dioxide emissions during handling, and organics were found to have the highest decomposition methane emissions. Targeted suggestions are given for source-separated CDW disposal GHG emission reduction based on the different emission characteristics. The combination of the BIM-based CDW IMS and the developed mathematical formulae were found to efficiently and accurately determine the CDW information and the associated GHG emissions, and therefore provide a practical guide to reducing the serious environmental damage generated by CDW disposal.

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1. Introduction

Because of the increased evidence associating greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) with global warming and climate change (Yan et al., 2010), reducing GHG emissions has become a global concern (Williams et al., 2012; Kaliyavaradhan and Ling, 2017; Bhattacharyya et al., 2013a). Primary concerns have been CO_2, CH_4 and N_2O emissions, with the respective concentrations having already reached 400 ppm, 1826 ppb and 326 ppb (Bhattacharyya et al., 2013b), a net increase of 142%, 253% and 121% since preindustrial times (Wang et al., 2017). As a result, most industry sectors are required to quantify and reduce CO_2, CH_4 and N_2O emissions.

Construction and demolition waste (CDW) end of life disposal methods such as landfill and incineration have contributed less than 6.6% to global GHG atmospheric emissions since 2010 (on Climate Change, IPCC). However, this is expected to grow significantly because of continuing industrialization and urbanization; for example, CDW accounts for around 46% of total waste in Europe, 20% of total solid waste in Japan, and 30%–40% of total municipal waste in China (Galvez-Martos et al., 2018; Lu et al., 2017a; Huang et al., 2018). Further, as global CDW is estimated to increase from 12.7 billion metric tonnes to 27 billion metric tonnes by 2050 (Andrade et al., 2018), actions are required now to restrict CDW GHG emissions. As HFCs, PFCs and SF_6 are seldom emitted from construction activities, the main CDW disposal GHG emissions are CO_2, CH_4 and N_2O (Li and Chen, 2017). Therefore, with the expected

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growth in CDW, the associated CO_2, CH_4 and N_2O emissions need to be accurately quantified so as to develop targeted and appropriate emission reduction measures.

To be able to accurately quantify and then control CDW end of life GHG emissions, precise CDW estimation methods are needed to clarify CDW information, such as CDW types, CDW quantities, and CDW locations (Peplow, 2017); however, current CDW and the associated GHG estimation methods have limitations as there are limited databases, inconvenient large data, and inaccurate traditional models (Won and Cheng, 2017; Akinade et al., 2018). Consequently, advanced technological solutions such as BIM software need to be harnessed. As BIM software provides a digital representation of the physical and functional characteristics of a facility, it has been widely used to improve building design quality, optimize construction schemes and manage CDW (Lu et al., 2017b). The technical benefits and innovative operation platform of BIM software also improve project life cycle sustainability (Chong et al., 2017), and ensure the advancement in quantification and reduction of environmental effects from the CDW management (Alwan et al., 2016).

However, even though BIM software has been used to determine CDW information and ensure some degree of CDW life cycle sustainability, the detailed BIM CDW information acquisition process and combining BIM technology with multiple GHG quantification mathematical formulae have attracted little research attention. In fact, as BIM generates 3-D digital simulations based on real project building information data (Bruno et al., 2018; Peng, 2016), which provides guidance on the management on project costs, material volumes, schedules, and environmental impacts (Crawley et al., 2008; Marsh, 2003), it lays the foundation to easily acquire and precisely estimate the CDW information (Akinade et al., 2018). Then, the mathematical formulae can be applied to accurately quantify CDW end of life disposal GHG emissions (Abdullah et al., 2013).

Therefore, in this paper, a BIM-based CDW information management system (IMS) is proposed to precisely estimate CDW types, quantities, and other associated information, which also clearly shows how the CDW information is derived from the BIM models. Mathematical estimation formulae with embedded CDW GHG emission factors for CO_2, CH_4 and N_2O are then applied to accurately quantify the CDW disposal GHG emissions. A case study is then given that examines fifteen different CDW disposal GHG emissions to demonstrate the efficiency and effectiveness of the proposed methodology, after which suggestions for reducing CDW disposal GHG emissions and managing source-separated CDW are given to ensure better environmental protection and sustainable development. In summary, this paper establishes a BIM-based CDW IMS and combines it with specific GHG mathematical formulae to derive detailed source-separated CDW information and disposal GHG emissions. Detailed GHG emission analyses and comparisons are made, and targeted emission reduction suggestions are given.

The overall structure and the methodological flows are illustrated in Fig. 1. As shown, in Section 2, previous research on CDW and the related GHG emission management is explored. In Section 3, the key issues associated with CDW information and GHG emission estimation are described. In Section 4, the BIM-based CDW IMS and the mathematical calculation formulae are established to determine the CDW disposal GHG emissions. In Section 5, a practical case is given to demonstrate the proposed methodology; result analyses and comparisons are conducted, and practical

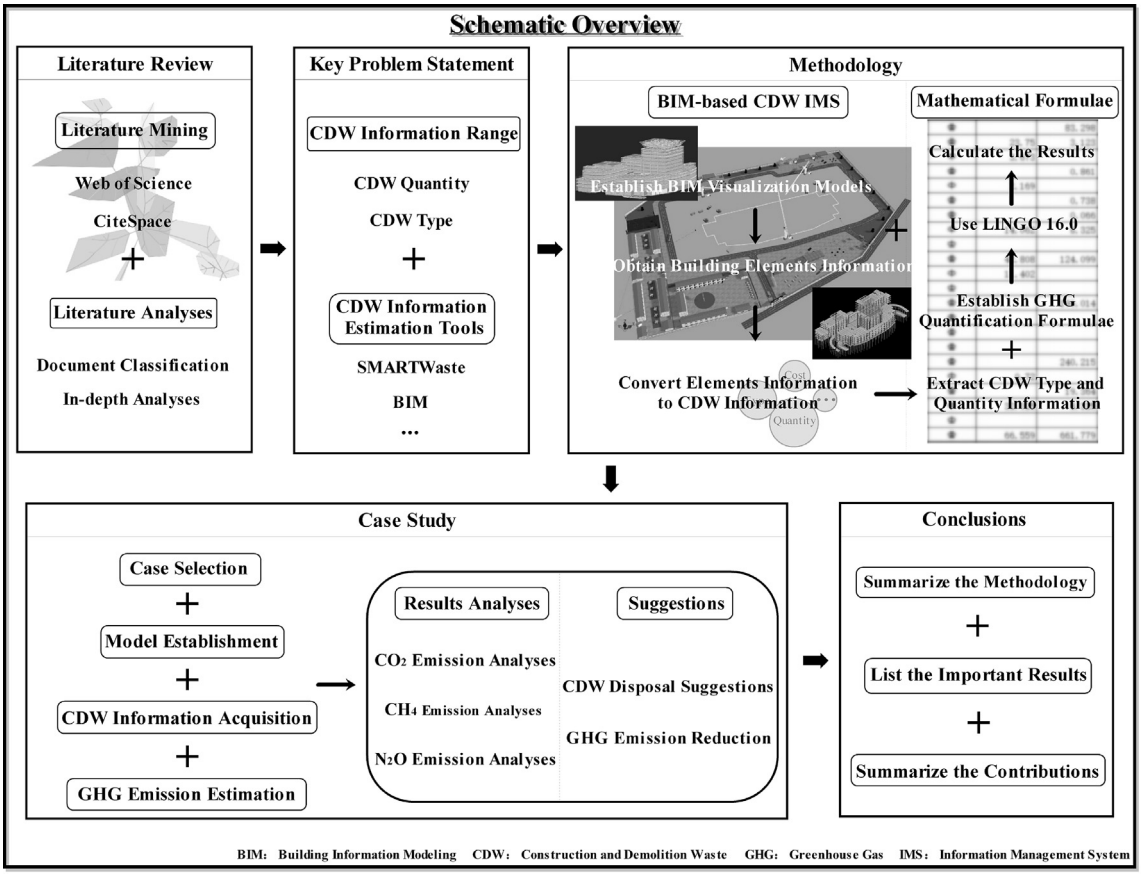

Fig. 1. Schematic overview.

suggestions are given to manage CDW and reduce the associated disposal GHG emissions. In Section 6, comprehensive conclusions are given based on the analyses and suggestions.

2. Literature review

In this section, a literature mining and analytical process is harnessed to identify the pertinent CDW disposal and associated GHG emission quantification research.

2.1. Literature mining

Because there has been extensive research on CDW problems, identifying the most useful methods and research development directions is difficult. Literature mining, however, can be used to identify the most related CDW management and associated GHG emission research as it is able to reveal the main trends and technological developments in the published research (De and Martin, 2002). Hundreds of previous research can be reviewed using literature mining process to analyze the trends and status in technological development (Xu and Li, 2016).

As keyword analyses identify core research ideas and themes (Liao, 2003), in this paper, keyword search was applied to the Web of Science database to explore the CDW trends. The search strings were set as TS=("A" AND "B") (Xu et al., 2017a), in this paper for "construction and demolition waste", from which 661 research papers were identified and downloaded, the data records for which comprised the research citation, title, author and abstract. CiteSpace software, a keyword trend classification technique, was then used to clarify the CDW disposal GHG emission trends (Chen, 2009), after which a cluster map and related analyses were generated from the 661 entries. As shown in Fig. 2, 23 clusters were generated, with five being found to be closely related to the focus of this paper, as highlighted in the figure and detailed below.

(1) Research on CDW management methods and the related environmental impact was collected under the ♯9 cluster label, "environmental management", with the associated keywords being life cycle assessment, carbon emissions, waste management, and construction and demolition waste management.
(2) Research on CDW management tools and techniques was collected under the ♯10 cluster label, "technique", with the associated keywords being construction and demolition waste, classification techniques, management tools, and designs.
(3) Research on environmental pollution associated with CO_2 emissions was collected under the ♯12 cluster label, "atmospheric CO_2", with the associated keywords being environmental pollution, carbon dioxide, and recycling and reuse.
(4) Research on current CDW GHG emission measurement methods was collected under the ♯16 cluster label, "methane production", with the associated keywords being impact assessment, greenhouse gas, organic carbon, and models.
(5) Research on CDW disposal emissions was collected under the ♯20 cluster label, "emissions", with the associated keywords being composting and recycling emissions.

The literature mining elucidated the previous CDW management methods and related GHG estimation trends. The CDW management tools and techniques were used, and the mathematical methods were employed to estimate CO_2 and methane emissions. An in-depth analyses of the research collected under these five cluster headings was then conducted.

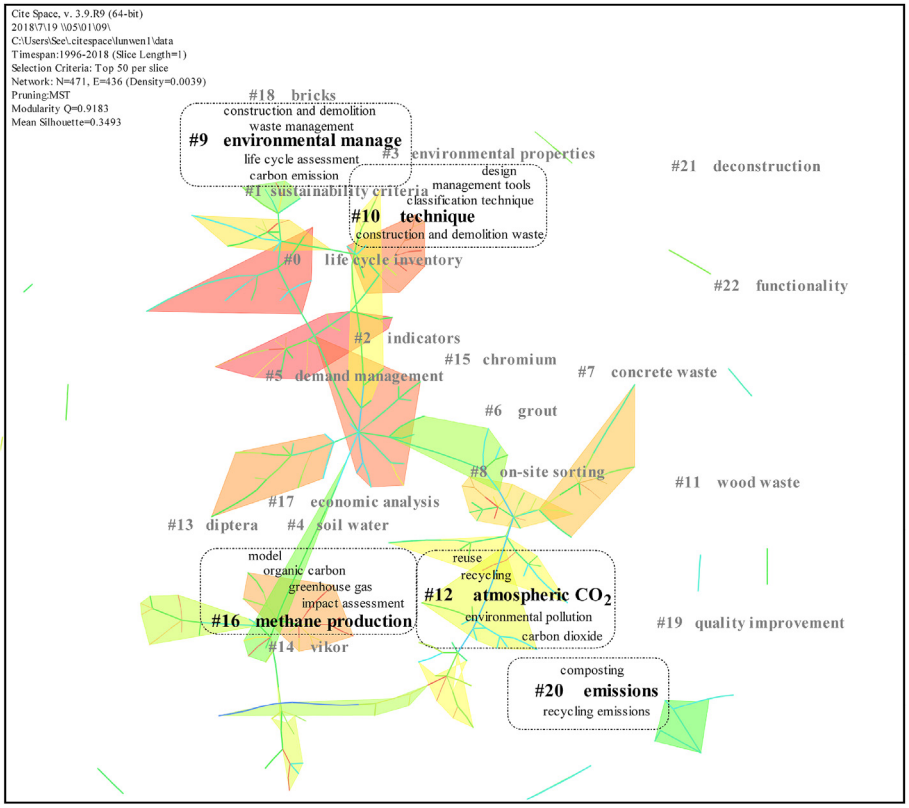

Fig. 2. Keyword analyses for the selected database.

2.2. In-depth analyses of literature

Several studies have investigated GHG emission reduction measures for some CDW types. Hossain and Chi (Hossain and Chi, 2017) conducted a life cycle assessment of construction industry wood waste disposal with a view to reduce the environmental impact; Fan and Miller (Fan and Miller, 2018) developed several mathematical models to minimize GHG emissions from different construction sector concrete types; and Teh et al. (Teh et al., 2017) estimated the carbon footprint of cement and concrete to explore methods to reduce excessive GHG emissions.

Several specific mathematical models and methods have been developed to estimate CDW quantities and the associated GHG emissions. Abanda et al. (Abanda et al., 2013) developed an integrated mathematical model to calculate construction waste quantities and the related GHG emissions in an attempt to identify the relationships between construction waste quantities and GHG emissions; and Vitale et al. (Vitale et al., 2016) developed a life cycle assessment method to estimate CDW quantities and its potential environmental harm with a particular focus on demolition waste disposal.

Several studies have employed advanced management tools such as BIM software to estimate CDW information and the related GHG emissions. Akinade et al. (Akinade et al., 2016) used evaluation criteria to identify the characteristics for 32 construction waste management tools, from which detailed features for existing CDW management tools were obtained; Liu et al. (Liu et al., 2015) used BIM software to establish a construction waste minimization framework, which focused on the construction waste generated in the design stage; Lu et al. (Lu et al., 2017b) used BIM software to estimate construction waste quantities, proving the accuracy of the BIM software; and Peng (Wang et al., 2018) combined a life cycle assessment method and BIM software to explore the carbon emissions from demolition waste.

CDW information and the associated GHG emission estimation methods have been explored; several models are developed to calculate specific CDW GHG treatment emissions, and multiple tools are employed to obtain accurate CDW information and manage the CDW disposal process. Therefore, as an extension of this previous research, this paper combines advanced techniques and mathematical formulae to quantify source-separated CDW disposal GHG emissions. First, an advanced BIM-based CDW IMS is established to extract the relevant CDW information, after which the mathematical formulae for the different GHGs are used to estimate the three main GHGs associated with the CDW disposal process. The results from this study can assist in the development of targeted, valid emission reduction measures for source-separated CDW disposal to reduce the environmental impact of CDW disposal GHG emissions.

3. Key problem statement

Most current methods used to extract CDW information have proven to be time-consuming, inaccurate, and complex; therefore, a new methodology is needed to solve current problems and lay the foundation for the quantification of the CDW disposal GHG emissions. To further illustrate the problem complexity, some key foci are given in this section.

3.1. CDW information range

The foundation of CDW disposal GHG emission quantification is to accurately identify the CDW types and quantities. First, with the increase in the quantities of CDW, its related treatment GHG emissions are also rise. Therefore, it is urgent and important to obtain accurate information on CDW quantities. Second, it is important to extract accurate information about the CDW types; organic, inorganic, inert, non-inert, recyclable and non-recyclable; to develop targeted CDW disposal and accurate GHG quantification measures. Third, as CDW can be generated from multiple building processes, it is also important to identify when, where and by which activities the CDW is generated. These CDW related information are quite essential for its GHG emission quantification and reduction. Because of the diverse characteristics of these information sources, acquiring precise CDW information has proven complicated, which in turn has meant that it has been difficult to quantify the associated GHG emissions and develop appropriate emission reduction schemes.

3.2. CDW information estimation tools

To understand how the proposed BIM-based CDW IMS improves CDW disposal emission problems, it is first necessary to examine the limits of the current CDW information estimation tools. Several CDW management tools have been developed to estimate CDW information; Site Methodology to Audit Reduced Target Waste (SMARTWaste), the Net Waste Tool (NWT), the BEDEC database, and BIM software. Even though the BEDEC database was established to store large amounts of CDW data, it does not have a CDW quantification function and cannot be used on different sites when other technology is also being used (Cheng and Ma, 2013). SMARTWaste, which was developed from previous British project statistical data, has been found to be unable to obtain sufficient and accurate CDW information; therefore, it has limited uses (Wong and Zhou, 2015). Because of these limitations, to improve applicability, accuracy and sufficiency, NWT, a CDW accounting tool, was designed to estimate CDW information; however, as this tool is only functional for large CDW quantities, it cannot be applied at the information estimation building design stage, and is unable to give a CDW whole-life assessment (Akinade et al., 2018). Therefore, most current CDW management tools are unable to provide information at the critical design stage, and while these CDW management tools have resolved some issues, some problems still exist. The main limitations of these existing tools are summarized as follows:

(1) The CDW information estimation application areas are limited;
(2) The information obtained is often insufficient and/or inaccurate;
(3) There is a lack of support for CDW lifecycle assessments;
(4) There is an inability to reflect the CDW information in the design stage;
(5) There is a lack of direct dimensions for the CDW information.

What is needed, therefore, is a technology that is able to provide accurate CDW information estimation across the complete CDW lifecycle. When BIM software has been applied to the construction industry, it has provided accurate quantification across different sites and in concert with other technologies. The building information and data obtained using BIM software has proven to be precise and sufficient and able to provide whole-life building information assessments, which can facilitate consistent decision-making at the early design stages and ensure whole life project sustainability (Saieg et al., 2017). Therefore, even though BIM software is focused on the building materials and elements rather than CDW, it could be used to resolve current CDW management problems and lay the foundation for more precise CDW information acquisition.

Based on the above analyses, this paper seeks to overcome existing CDW information management problems by establishing a

BIM-based CDW IMS that not only overcomes the inaccuracies and lack of whole-life assessments in most existing tools, but also provides detailed CDW information acquisition process, which ensures the information obtained is directly related to CDW and required for its GHG emission quantification. Then, by combining this precise CDW information with the appropriate mathematical formulae, accurate GHG emission quantification for CDW end of life disposal are obtained to allow for the development of valid, targeted emission reduction strategies.

4. Methods

A BIM-based CDW IMS combined with appropriate mathematical formulae is developed to accurately quantify the CO_2, CH_4 and N_2O GHG emissions from source-separated CDW end of life disposal.

4.1. BIM-based CDW information management system

In this section, the BIM-based CDW IMS is introduced to provide precise CDW information, and the detailed CDW information acquisition process is also illustrated. As seen in Fig. 3, the BIM-based CDW IMS has three stages; a building and demolition stage, a BIM model establishment stage, and a CDW information acquisition stage. The building and demolition process in the first stage includes the basic construction, the main structure

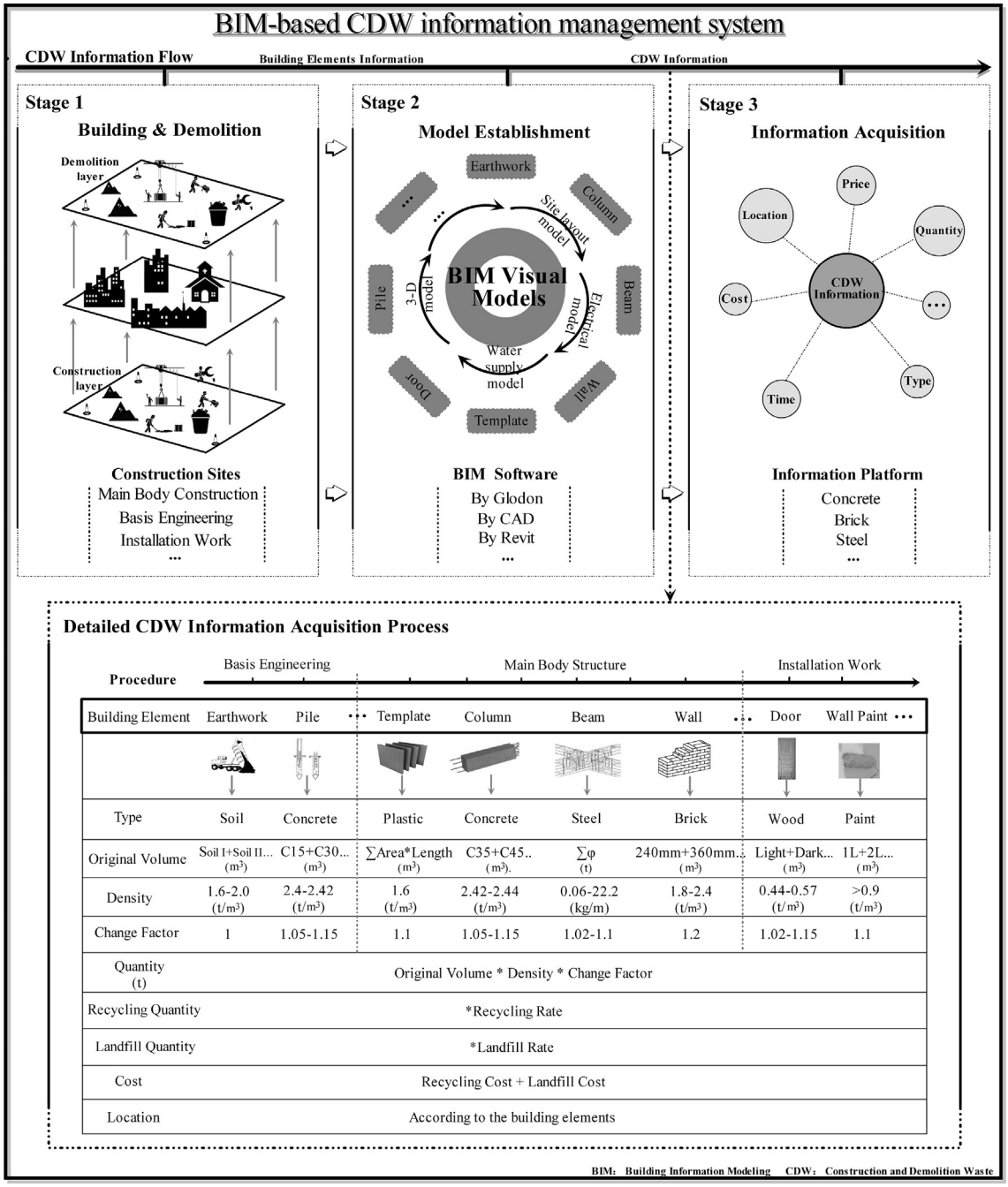

Fig. 3. CDW information management system.

construction, which would generate multiple building elements, such as brick walls, concrete columns, beams and doors, and each of them generates a certain quantity of CDW (Stage 1 in Fig. 3).

In Stage 2, the BIM are employed to develop digital models based on the actual building dimensions to manage the whole life of a building, from which detailed information about the specific building elements is obtained. The BIM includes multiple software applications such as Autodesk Rvit Architecture and Glodon that allows it to generate multiple BIM models. Therefore, using the proposed BIM models, users are able to manipulate the complete building process by developing 3D simulations of the columns, walls, doors and other components that include information on the width, area, and material types based on the actual situation. Therefore, the proposed BIM models can obtain accurate, sufficient, timely information about all building elements (Stage 2 in Fig. 3).

Finally, in Stage 3, after some conversions, the CDW information is extracted from the BIM model building element information, as shown in Stage 3 in Fig. 3. The detailed conversion process from the building elements information to the CDW information is also shown in Fig. 3 (from the detailed CDW information acquisition process). As illustrated, the CDW types corresponding to the individual building elements are determined and the original volumes obtained as the sum of all models for this CDW type. The final quantities for each CDW type are then converted by multiplying the density and change factors. The recycling and landfill quantities can then be determined based on the different rates.

The disposal costs comprise multiple costs associated with recycling and landfill, and the CDW locations are based on the building element locations. As the information for this system can be pre-defined based on the actual situation, the CDW information can be supplied in real-time. Therefore, the proposed BIM-based CDW IMS provides valid, sufficient and precise information that is directly related to the CDW, from which the associated CDW disposal GHG emissions can be precisely quantified, thereby laying the foundation for targeted emission reduction proposals.

4.2. CDW disposal GHG emissions

As the CDW disposal GHG emissions that cause the most environmental damage are CO_2, CH_4 and N_2O, the emission processes for only these three gases are discussed in this section. Based on the composition of reverse logistics established by Xu et al., this paper proposes the CDW end of life disposal reverse channels (Xu et al., 2018). As seen in Fig. 4, CDW disposal reverse logistics are shown and compared with material production forward logistics; the detailed CDW end of life disposal GHG emissions are also illustrated, from which it can be seen that multiple CDW disposal centers are contained. First, the classification center (CC) sorts the CDW into recyclable and unrecyclable elements, with the recyclable CDW being sent to the second-materials store (SMS) to be roughly sorted into smaller parts, after which it is sent to the recycling plant (RP) to be remanufactured and reused; the unrecyclable CDW is sent directly to landfill sites (LS). Therefore, the main CDW disposal GHG emission sources are transportation emissions, center handling emissions, and the decomposition emissions per landfill year (AbdelhadiMakan et al., 2012). The transportation emissions (CO_2, CH_4 and N_2O) are generated when the construction site (CS) CDW is transported from the CS to the CC, the CC to the SMS, the SMS to the RP, and the CC to the LS. The handling CO_2 is generated during CC classification, SMS sorting, RP recycling, and at the LS. And the CDW decomposition emissions are generated over the long CDW landfill decomposition period.

Of these three GHGs, the N_2O emissions contribute most to the greenhouse effect. Table 1 shows the warming potentials of these three GHGs, from which it can be seen that the N_2O effects are far greater than the CH_4 and CO_2 effects, and the CH_4 effects are 25 times greater than CO_2 effects (Li and Chen, 2017). Li and Chen proposed the warming potentials and focused on assessing the energy consumption and carbon dioxide emissions from construction projects, of which the research scope focused on the construction and implementation phase. Based on their research,

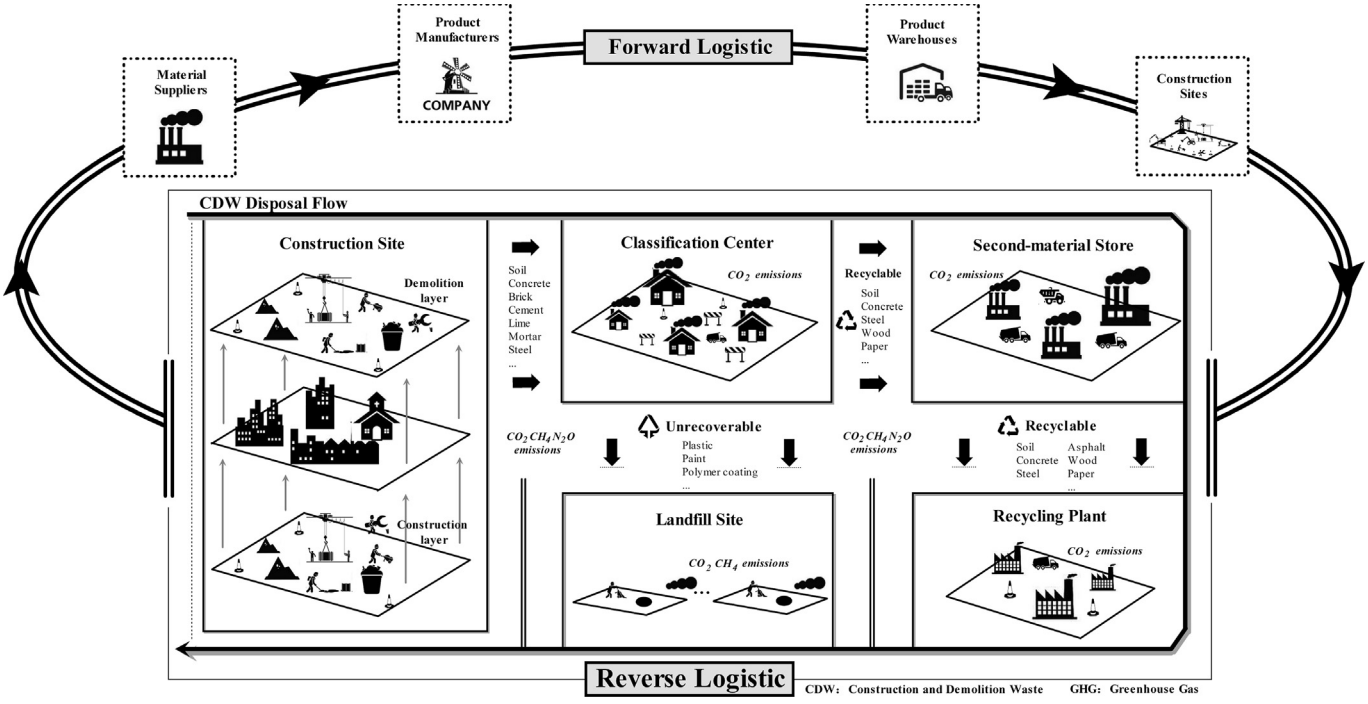

Fig. 4. CDW end of life management and GHG emissions.

Table 1
GHG warming potential.

Gas type	GWP value (kg CO_2/kg)		
	20 years	100 years	500 years
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153

[a] Source: (Li and Chen, 2017)

this paper proposes advanced BIM-based CDW IMS and studies the three GHG emissions from the CDW end of life disposal.

Based on the CDW disposal GHG emission analyses above, detailed GHG emissions for the source-separated CDW can be obtained using the following mathematical notations:

List of notations:

Sets
JSet of transportation modes, J = {1,2,⋯,*J*}
KSet of CDW type, K = {1,2,⋯,*K*}
Indices:
jTransportation modes index
kCDW typle index
parameters:
D_{bs}Distance from the CS to the CC (unit: km)
D_{sc}Distance from the CC to the SMS (unit: km)
D_{cr}Distance from the SMS to the RP (unit: km)
D_{sl}Distance from the CC to the landfill site(LS) (unit: km)
*DOC*Degradable organic carbon fraction of CDW
DOC_FFraction of actual degradable carbon
E_{CO2}Total CO_2 emissions associated with CDW disposal process (unit: tonne)
E_{CH4}Total CH_4 emissions associated with CDW disposal process (unit: tonne)
$E_{de}$$CH_4$ emissions associated with CDW landfill decomposition (unit: tonne)
$e_{d,j}$$CO_2$ transportation emissions for mode j per unit (unit: tonne/tonne-km)
$e_{dm,j}$$CH_4$ transportation emissions for mode j per unit (unit: tonne/tonne-km)
$e_{dn,j}$$N_2O$ transportation emissions for mode j per unit (unit: tonne/tonne-km)
$E_h$$CO_2$ emissions from CDW handling processes (unit: tonne)
$p_{l,k}$Unit CO_2 emissions from waste k landfill process at LS (unit: tonne/tonne)
$p_{r,k}$Unit CO_2 emissions from waste k recycling process at RP (unit: tonne/tonne)
E_{total}:Total GHG emissions from CDW disposal process (unit: tonne)
$E_{tr}$$CO_2$ emissions from CDW transportation process (unit: tonne)
$E_{trm}$$CH_4$ emissions from CDW transportation process (unit: tonne)
$E_{trn}$$N_2O$ emissions from CDW transportation process (unit: tonne)
FCH_4 concentration of landfill gas
kConstant for methane reaction rate
*MCF*Methane correction factor
*OX*Oxidation factor
$Q_{bs,k}$Quantity of mixed waste k transported from the building site to the CC (unit: tonne)
$Q_{cr,k}$Quantity of source-separated waste k transported from the SMS to the RP (unit: tonne)
$Q_{sc,k}$Quantity of source-separated waste k transported from the CC to the SMS (unit: tonne)
$Q^t_{sl,k}$Quantity of source-separated waste k transported from the CC to the LP (unit: tonne)
RCH_4 recovered value
TCDW landfill year

4.3. Detailed CO_2 emission calculation

This section details the CO_2 emission calculation formulae for the source-separated CDW. As mentioned, the CDW CO_2 emissions are the CDW transportation emissions and the CDW handling emissions at each disposal center (Xu et al., 2017b).

Based on the "2006 IPCC national greenhouse gas inventories programme", the CO_2 emissions for these different activities are C = ∑l,m,nADl,m,n•EFl,m,n (Agency, 2006), where C is the CO_2 emissions, *AD* is the CDW treatment, *EF* is the carbon emission factor, l is the region parameter, m is the method used and n is the fuel type. Therefore, based on this calculation formula, the detailed CO_2 emission expressions are as follows:

Total **CO_2** emissions from the CDW disposal process. The total CO_2 emissions are the sum of the transportation and handling emissions, which can be expressed as:

$$E_{CO_2} = E_{tr} + E_h \tag{1}$$

where E_{tr} are the CDW transportation emissions and E_h are the CDW handling emissions.

E_{tr} = transportation emissions from the CS to the CC + transportation emissions from the CC to the SMS + transportation emissions from the SMS to the RP + transportation emissions from the CC to the LP.
E_h = classification emissions in the CC and SMS + recycling emissions in the RP + landfill emissions in the LS.

The detailed calculations and explanations are as follows:

(1) **CO_2 transportation emissions.** Two transportation modes are considered; large and small diesel trucks; both of which use diesel; therefore, based on the transportation modes and distances, the transportation CO_2 emissions are (Xu et al., 2016):

$$E_{tr} = \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{bs,k}\cdot e_{d,j}\cdot D_{bs} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sc,k}\cdot e_{d,j}\cdot D_{sc} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{cr,k}\cdot e_{d,j}\cdot D_{cr} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sl,k}\cdot e_{d,j}\cdot D_{sl} \tag{2}$$

where $\sum_{k=1}^{K}\sum_{j=1}^{J} Q_{bs,k}\cdot e_{d,j}\cdot D_{bs}$ are the transportation emissions from the building site to the CC, $\sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sc,k}\cdot e_{d,j}\cdot D_{sc}$ are the transportation emissions from the CC to the SMS, $\sum_{k=1}^{K}\sum_{j=1}^{J} Q_{cr,k}\cdot e_{d,j}\cdot D_{cr}$ are the transportation emissions from the SMS to the RP for waste recycling, and $\sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sl,k}\cdot e_{d,j}\cdot D_{sl}$ are the transportation emissions from the CC to LP for waste landfill.

(2) **CO_2 handling emissions.** The CO_2 handling emissions include the classification emissions at the CC, the SMS, the recycling emissions at the RP and the landfill emissions in the LS; therefore, the CDW handling CO_2 emissions are:

$$E_h = \sum_{k=1}^{K} Q_{sc,k} \cdot p_{r,k} + \sum_{k=1}^{K} Q_{sl,k} \cdot p_{l,k} \tag{3}$$

where $\sum_{k=1}^{K} Q_{sc,k} \cdot p_{r,k}$ are the recycling emissions and $\sum_{k=1}^{K} Q_{sl,k} \cdot p_{l,k}$ are the landfill emissions. The landfill emissions here refer to the physical emissions generated during the landfill process rather than the chemical biogenic CO_2 emissions generated from the organic matter digestion as these are not classified as a greenhouse gas (Minoglou and Komilis, 2013).

4.4. Detailed CH_4 emission calculation

This section details the CH_4 emission formulae for the source-separated CDW. Methane emissions are generated from waste decomposition, fossil fuel use, biomass incineration, rice cultivation, and domestic ruminants (Kirschke et al., 2013), of which the fossil fuel use and landfill site waste decomposition are specifically related to CDW disposal. Therefore, the CH_4 emissions referred to here are the CDW transportation emissions and the CDW landfill decomposition emissions. The detailed methane emission expressions are as follows:

Total CDW disposal **CH_4** emissions. Based on the above analyses, the total CDW disposal CH_4 emissions are the sum of the transportation and decomposition emissions, which can be expressed as:

$$E_{CH_4} = E_{trm} + E_{de} \tag{4}$$

where E_{trm} are the transportation methane emissions and E_{de} are the decomposition methane emissions.

E_{trm} = transportation emissions from the CS to the CC + transportation emissions from the CC to the SMS + transportation emissions from the SMS to the RP + transportation emissions from the CC to the LP.
E_{de} = decomposition emissions during the long landfill years.

Detailed calculations and explanations are given in the following.

(1) **CH_4 CDW transportation emissions.** As with the CO_2 emissions, the CH_4 transportation emissions are generated from the large and small diesel trucks; therefore, the CH_4 transportation emissions are:

$$E_{trm} = \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{bs,k} \cdot e_{dm,j} \cdot D_{bs} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sc,k} \cdot e_{dm,j} \cdot D_{sc} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{cr,k} \cdot e_{dm,j} \cdot D_{cr} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sl,k} \cdot e_{dm,j} \cdot D_{sl} \tag{5}$$

which also include the emissions from center to center.

(2) **CH_4 CDW decomposition emissions.** Decomposition methane emissions are generated from some non-inert CDW decomposition over the long landfill years at the LS. The developed FOD method presented by the IPCC explains how the methane emissions change over time, the methane emission calculation formula for which are (Agency, 2006; Kumar et al., 2004):

$$E_{de} = \sum_{k=1}^{K}\sum_{t=1}^{T} \left(e^{-(T-1)k} - e^{-Tk}\right) \cdot Q_{sl,k} \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot \left(\frac{16}{12} - R\right) \cdot (1 - OX) \tag{6}$$

where the methane correction factor MCF depends on the type of waste and the landfill method. The actual degraded fraction DOC_F depends on the CDW landfill type.

4.5. Detailed N_2O emission calculation

The N_2O emission sources are natural emissions and human activity emissions (Frutos et al., 2018), of which the human caused N_2O emissions are from agriculture, burning biomass, industrial processes, fossil fuel combustion, and human waste treatment in WWTPs (STOCKER et al., 2013). Of the multiple N_2O emission sources, only fossil fuel combustion is related to CDW disposal. Therefore, the only N_2O emissions in this paper are generated in the CDW transportation process; that is, transportation emissions from the CS to the CC, the CC to the SMS, the SMS to the RP, CC to the LP, which are expressed as follows:

$$E_{trn} = \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{bs,k} . e_{dn,j} . D_{bs} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sc,k} . e_{dn,j} . D_{sc} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{cr,k} . e_{dn,j} . D_{cr} + \sum_{k=1}^{K}\sum_{j=1}^{J} Q_{sl,k} . e_{dn,j} . D_{sl} \tag{7}$$

In summary, based on the above analyses, the total CDW disposal GHG emissions are:

$$E_{total} = E_{tr} + E_h + E_{trm} + E_{de} + E_{trn} \tag{8}$$

4.6. Methodology summary

The proposed methodology establishes a CDW IMS based on BIM software to first obtain precise CDW information, after which the GHG emission mathematical formulae are used to quantify the three CDW disposal GHG emissions.

The established CDW IMS overcomes several CDW management problems. First, the BIM software in the CDW IMS has quantification functions so that the CDW IMS can be applied at different sites and can handle complex data. Second, as the established BIM models simulate the construction, the building information and data is accurate. Third, as the 3D visualization BIM technology can simulate the project before construction, the CDW quantities and information are able to be estimated in the building design stage. Finally, the established CDW IMS provides detailed building element information to the CDW information conversion process, which guarantees the IMS data is directly related to the CDW. Therefore, the proposed CDW IMS is a practical, valid system for obtaining sufficient, precise and real-time CDW information.

Then, to quantify the specific CDW disposal GHG emissions based on the IMS information, mathematical formulae for the three GHG emissions are applied to obtain the source-separated CDW CO_2 CH_4 and N_2O emissions, which avoid the uncertainty in some previous studies caused by mixing the CDW. Because the original data from the CDW IMS is accurate and detailed, the determined

CO_2 CH_4 and N_2O emissions for each CDW type are precise.

The methodology proposed in this section is applied to a real-life situation to further explore its applicability, efficiency and effectiveness.

5. Case study

In this section, a practical case is introduced to derive the CDW information, quantify the specific GHG emissions, give detailed CDW disposal suggestions, and provide guidance for similar real-life cases. The data for different CDW and its associated GHG emissions were obtained from the China Construction Eighth Engineering Corporation Limited (CCEBCL).

5.1. Case representation

CCEBCL is a large key construction group affiliated with the China Construction Corporation. The real-life case is a school complex building project (SCBP) in Pixian city, Sichuan Province, China. The SCBP is a 10 storey building with 9 floors above ground and a 1-floor basement. The building has a cast-in-place frame structure, with a total construction area of 39570.5 square meters, and an anti-seismic intensity of 7. To better understand the SCBP, the general case study project information is summarized in Table 2.

5.2. Application of the methodology

The proposed methodology was applied over four main phases; a BIM-based CDW IMS application phase, a CO_2 emission quantification phase, a CH_4 emission quantification phase and a N_2O emission quantification phase. In the BIM-based CDW IMS application phase, visual BIM models of the SCBP were developed and detailed CDW information were obtained from the CDW IMS. In the CO_2, CH_4 and N_2O emission quantification phases, precise emission quantities were quantified for the 15 CDW types generated at the SCBP site. Detailed descriptions of the four phases are given in the following subsections.

5.2.1. Phase I: BIM-based CDW IMS application

SCBP BIM models were established and SCBP CDW information was obtained for the BIM-based CDW IMS application.

First, using the common BIM composition software applications, Glodon and Autodesk Revit Architecture, and the CCEBCL construction drawings, a construction site layout model was developed to simulate the building construction site (the first part in Fig. 5). The multidimensional visual model of the building's main structure was then built using the Autodesk Revit Architecture software (the second part in Fig. 5). Some building sub-models were also developed, in which the civil engineering models correspond to the CDW generated by the building and the installation models correspond to the CDW generated by pipes and wires (the third part in Fig. 5.)

Comprehensive SCBP information was then obtained from the established BIM models; the building schedule, the site layout, the materials information; from which the building element types and volumes were extracted to estimate the CDW. To begin with, after the SCBP element classifications, the elements were divided into 15 different types such as columns, beams, and doors and then were compared to the proposed CDW IMS to determine the CDW, for which there were also 15 types. The 15 types of CDW was shown in Table 4 (Nos.1–15), in which light steel was a new type of construction material that was light, dust-proof and waterproof. Then, the CDW quantities were estimated based on the sorted original building element volumes (Table 4). Before estimating the detailed CDW quantities, density information for the weight calculations and the quantity change factor values were needed. Therefore, based on (Llatas, 2011) and (Cheng and Ma, 2013), the values for the 15 CDW densities and quantity change factor values were determined (Table 3); however, as different building projects have different values, the values were altered to fit the actual situation. After calculations, the detailed source-separated CDW quantities generated by the building project were determined (Table 4). Finally, as shown in the CDW IMS, the CDW recycling and landfill rates were determined based on the actual recycling situation in Pixian; the recycling rate was set at 10% and the landfill rate was set at 90% (Wu et al., 2016); and then the CDW recycling and landfill quantities were calculated (Table 4). Therefore, Table 4 shows the CDW types, the original volumes, the final calculated CDW quantities, and the CDW recycling and landfill quantities. Some other CDW information from the CDW IMS is not listed here, such as the CDW costs and the CDW prices, as these are not related to the CDW disposal GHG emission quantification.

Table 2
Project information.

Name	Information
Construction area (m^2)	39570.5
Floors	10
Basement	1
Structure type	Frame
Local environment	Urban
Anti-seismic degree	7

5.2.2. Phase II: CO_2 emission quantification

Phase II quantified the specific CO_2 transportation and handling emissions for the 15 CDW types. To calculate the CO_2 emissions for each type of CDW, the practical parameter values were collected before applying the formulae. Based on the practical distances in Pixian City, the specific distances between the CDW disposal centers were estimated (Table 5). Table 6 shows the CDW handling emissions, which include the CDW recycling, and the landfill emissions. The CDW emission factor values were extracted from Bok et al. (2014) and Turner et al. (2015). The emission factor values for the cement, lime, and mortar were determined based on inflammable materials; however, as these may not be accurate, users could apply different values for these parameters based on their own judgements. Two transportation modes were considered, the CO_2 emission factors for which are shown in Table 7. Therefore, based on the above parameters, the detailed CDW end of life disposal CO_2 emissions were obtained.

5.2.3. Phase III: CH_4 emission quantification

Phase III quantified the specific CH_4 transportation emissions and the decomposition emissions for the 15 CDW types. In this case, the non-inert CDW that emits CH_4 during the decomposition process were wood, paper, and four CDW organics; paint, polymer coating, plastic, and asphalt. To quantify the CH_4 transportation emissions, the distances (Table 5) between the CDW disposal centers were determined, the associated CH_4 transportation emission factors for which are shown in Table 7. Along with some parameters extracted from previous papers for comparison, the parameters for the CH_4 decomposition emission calculations are shown in Table 8. Different from previous research, the DOC_F in this paper was determined based on the CDW landfill type to ensure more accurate calculations (Lee et al., 2017). The MCF was based on the landfill situation (Du et al., 2017) and was valued 1 in this paper. Based on the above parameters, the detailed CH_4 emissions were determined.

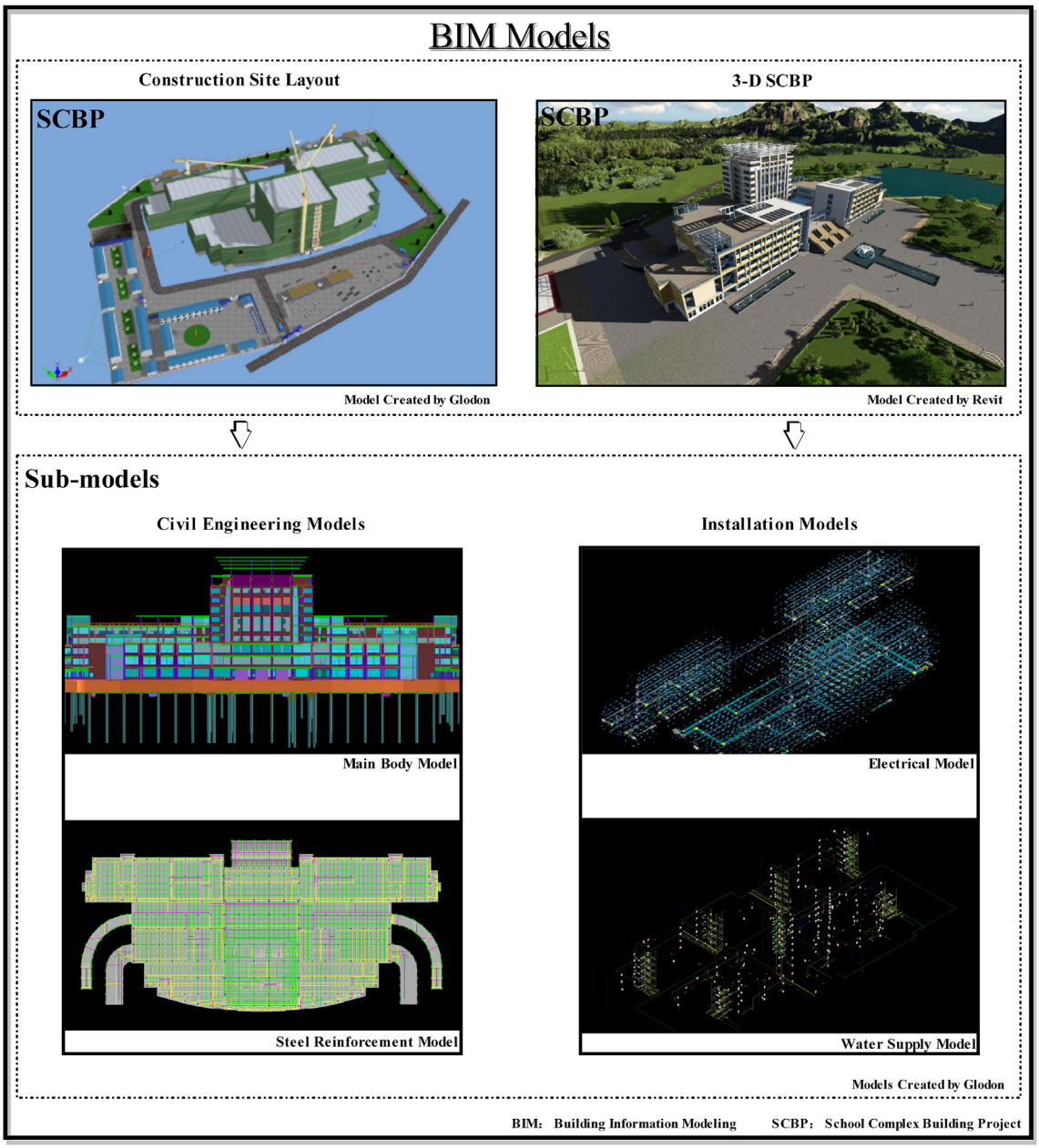

Fig. 5. BIM models.

5.2.4. Phase IV: N_2O emission quantification

Phase IV quantified the specific N_2O transportation emissions for the 15 CDW types, the factors for which are shown in Table 7 (Fan et al., 2018). Based on the transportation emission factors, the N_2O transportation emissions were obtained and the total N_2O emissions were quantified.

5.3. Calculation results

After the data collection, LINGO software was used to calculate the specific CDW GHG emissions. As LINGO software has high efficiency, high accuracy, and high speed, it was deemed ideal for the GHG quantifications in this paper. After inputting the data into LINGO 16.0, the values for the transportation CO_2, CH_4, and N_2O emissions, the CO_2 handling emissions, and the CH_4 decomposition emissions were obtained. (Table 9, Table 10 and Table 11).

As can be seen from Table 9, the 15 CDW types emitted 596 tonnes of CO_2 during transportation and 11660.35 tonnes of CO_2 during handling. Concrete had the highest CO_2 transportation emissions at 280.9 tonnes and the highest CO_2 handling emissions at 7239.6 tonnes, and asphalt had the second highest CO_2 emissions at 2902.7 tonnes. As shown in Table 10, the total CH_4 transportation emissions were 0.18 tonnes, the total CH_4 handling emissions were 8.16 tonnes for 1 landfill year, 31.1 tonnes over 20 years, and 31.4 tonnes over 50 years. Concrete had the highest CH_4 transportation emissions at 0.085 tonnes, and the organics emitted the highest CH_4 decomposition emissions at 8 tonnes for 1 year, 30.5 tonnes over 20 years, and 30.84 tonnes over 50 years. Table 11 shows that concrete had the highest N_2O transportation emissions at 0.013 tonnes.

Table 3
Necessary values for the CDW quantity estimation.

Material type	Density (tonne/m^3)	Change factor
Soil	1.74	1
Concrete (C15 C20 C30 C35 C40 C45)	2.4–2.44	1.1
Brick	1.9	1.2
Cement	2	1.2
Lime	3.3	1.2
Mortar	2	1.1
Steel	–	1.1
Ceramic tile	2.7	1.1
Paint	–	1.1
Polymer coating	–	1.1
Plastic	1.6	1.1
Wood	–	1.15
Paper	–	1.15
Asphalt	1.2	1.1
Plaster	0.9	1.2

Table 5
Distances between CDW disposal centers.

Distances (km)	CS	SC	SMS	RP	LS
CS	–	26	–	–	–
SC	26	–	18	–	35
SMS	–	18		20	–
RP	–	–	20	–	–
LS	–	35	–	–	–

5.4. Discussion

In this section, detailed analyses on the above results is first given for the specific GHG emission distributions, after which targeted suggestions for CDW GHG emission reduction and end of life management are provided to reduce the CDW disposal environmental impact and achieve sustainability.

5.4.1. Results analyses

From the above GHG emission results, it can be seen that the CO_2, CH_4, and N_2O transportation emissions were relatively small, with the concrete CDW having the highest CO_2, CH_4, and N_2O emissions. Transportation emissions are generally related to transportation mode, distance, and CDW quantities; however, when there is the same transportation mode and the same distance, the transportation emissions are directly related to the CDW quantities; therefore, as there were large CDW concrete quantities, it had the highest GHG transportation emissions.

From a comparison of the CDW transportation, handling, and long-term decomposition emissions, it was found that the handling and decomposition emissions were the highest, with concrete and organics having the highest respective CO_2 and CH_4 emissions. As there were no other N_2O emissions except for transportation, an in-depth analyses was conducted to further explore the interactions between the CO_2 handling and CH_4 decomposition emissions for the 15 CDW types. To do this, the CDW quantity percentages and the associated CO_2 handling and CH_4 decomposition emissions were calculated, as shown in Table 12 and Table 13. The associated emission distributions for each CDW type are shown in Fig. 6 and Fig. 7. 5.4.1.1. CO_2 emissions.

Fig. 6 details the CDW quantity and the associated CO_2 handling emission distributions. As shown in Fig. 6, there were 8 CDW types with quantities greater than 1000 tonnes and 7 CDW types with quantities less than 200 tonnes. Based on this division, the following conclusions were made.

(1) **Of the small CDW quantities, polymer coating had the greatest emissions.** From Table 12 and Fig. 6, it can be seen that even though the 36.52 tonnes of polymer coating made up only 0.03% of the total CDW, it emitted 76 tonnes of CO_2 or 0.65% of the total CO_2 handling emissions. Therefore, while the quantities of polymer coating were relatively small, it had comparatively high capacity to emit CO_2. Further, there were 1.1 tonnes of CO_2 emissions from the polymer coating recycling process, which was only 0.07% of the total recycling emissions; however, there were 74.9 tonnes of CO_2 emissions in the polymer coating landfill process, which was 7.5% of total CO_2 landfill emissions.

(2) **Plaster emitted very little CO_2.** While there were 149.3 tonnes of plaster CDW; 0.14% of the total; there were only

Table 4
Detailed information for the CDW.

No.	Material type	Remark	Original data	Unit	Calculated quantities (tonne)	Recycling quantities (tonne)	Landfill quantities (tonne)
1	Soil	–	5772.2	m^3	10043.6	1004.36	9039.24
2–1	Concrete	C15	91.91	m^3	242.6	24.26	218.34
2–2	Concrete	C20	138.6	m^3	365.9	36.59	321.21
2–3	Concrete	C30	14477.3	m^3	38379.3	3837.93	34541.37
2–4	Concrete	C35	477.8	m^3	1271.9	127.19	1144.71
2–5	Concrete	C40	384.4	m^3	1031.7	103.17	928.53
2–6	Concrete	C45	3610.8	m^3	9691.4	969.14	8722.26
3	Brick	–	5308.8	m^3	12104.1	1210.41	10893.69
4	Cement	–	3412.5	m^3	8190	819	7371
5	Lime	–	2.5	m^3	9.9	0.99	8.91
6	Mortar	–	8939.1	m^3	19666	1966.6	17699.4
7–1	Steel	$d \leq 10$ mm	1018.1	t	1119.9	111.99	1007.91
7–2	Steel	12 mm $\leq d \leq$ 16 mm	760.81	t	836.9	83.69	753.21
7–3	Steel	$d >$ 16 mm	1142.3	t	1256.5	125.65	1130.85
7–4	Light steel	–	8.4	t	9.24	9.24	8.32
8	Ceramic tile	–	771.1	m^3	2290.2	229.02	2061.18
9	Paint	–	561.3	kg	0.62	0.062	0.558
10	Polymer coating	–	33.2	t	36.52	3.652	32.868
11	Plastic	–	25.7	m^3	45.2	4.52	40.68
12	Wood	–	29.4	t	33.8	3.38	30.42
13	Paper	–	339	kg	0.39	0.039	0.351
14	Asphalt	–	1047.1	m^3	1382.2	138.22	1243.98
15	Plaster	–	138.2	m^3	149.3	14.93	134.37

Table 6
CDW CO_2 handling emission factors.

No.	Material type	CDW recycling CO_2 emission factor (tonne/tonne)	CDW landfill CO_2 emission factor (tonne/tonne)
1	Soil	0.041	0.02
2	Concrete	0.25	0.13
3	Brick	0.02	0.03
4	Cement	0.02	0.02
5	Lime	0.02	0.02
6	Mortar	0.02	0.02
7	Steel	0.53	0.03
8	Ceramic tile	0.025	0.018
9	Paint	0.364	2.25
10	Polymer coating	0.3	2.28
11	Plastic	0.339	0.02
12	Wood	0.502	0.05
13	Paper	1.58	2.25
14	Asphalt	0.3	2.3
15	Plaster	0.059	0.02

Table 7
Transportation emission factors for the different modes.

Transportation mode	CO_2 emission factor (tonne/(tonne-km))	CH_4 emission factor (tonne/(tonne-km))	N_2O emission factor (tonne/(tonne-km))
By big truck	1.68E-04	1E-09	4E-09
By small truck	1.60E-05	1E-09	4E-09

Table 8
Necessary parameters for calculating the decomposition CH_4 emissions.

	K	DOC	DOC_F			F	R	OX
			wood	paper	organics			
Du (Wu-Peng et al., 2006)	Not used	6.50%	0.6	0.6	0.6	0.5	0	0
Peng (Du et al., 2017)	0.3	6.50%	0.5	0.5	0.5	0.5	0	0.1
This paper	0.3	6.50%	0.47	0.21	0.6	0.5	0	0.1

Table 9
CO_2 emission calculation results.

NO.	Material type	Transportation emissions (tonne)	Recycling emissions (tonne)	Landfill emissions (tonne)	Total emissions (tonne)
1	Soil	55.3	41.2	180.8	222
2	Concrete	280.9	1274.6	5965	7239.6
3	Brick	66.7	24.2	326.8	351
4	Cement	45.1	16.4	147.4	163.8
5	Lime	0.055	0.02	0.18	0.2
6	Mortar	108.4	39.3	353.9	393.2
7	Steel	17.8	170.8	87	257.8
8	Ceramic tile	12.6	5.7	37.1	42.8
9	Paint	0.0034	0.02	1.26	1.28
10	Polymer coating	0.2	1.1	74.9	76
11	Plastic	0.25	1.5	0.82	2.32
12	Wood	0.19	1.7	1.53	3.23
13	Paper	0.0021	0.06	0.79	0.85
14	Asphalt	7.6	41.5	2861.2	2902.7
15	Plaster	0.82	0.88	2.69	3.57
Total		596	1618.2	10042.2	11660.35

3.57 tonnes of associated CO_2 emissions, which was only 0.03% of total CO_2 emissions. Therefore, as shown in Fig. 6, plaster emitted very little recycling and landfill CO_2. Therefore, although the quantities of plaster are the largest in the smaller quantities CDW, it had comparatively low capacity to emit CO_2.

(3) **Of the large CDW quantities, concrete had the highest emissions.** From Table 12 and Fig. 6, of the 8 large quantity CDW, concrete made up 47.14% of total CDW and had the largest CO_2 handling emissions at 7239.6 tonnes, which was 62.09% of total emissions. Concrete recycling also resulted in 1274.6 tonnes of CO_2, or 78.73% of the total recycling emissions, and the concrete in the landfill process made up 5965 tonnes of CO_2, or 59.4% of the total landfill emissions. Therefore, as one of the major part of CDW, concrete CDW was found to have the highest CO_2 emissions in the CDW handling.

Table 10
CH_4 emission calculation results.

Values	Transportation emissions (tonne)	Landfill emissions (tonne)			
		1 year	20 years	50 years	100 years
Soil	0.02	–	–	–	–
Concrete	0.085	–	–	–	–
Brick	0.02	–	–	–	–
Cement	0.014	–	–	–	–
Lime	0.16E-04	–	–	–	–
Mortar	0.033	–	–	–	–
Steel	0.0054	–	–	–	–
Ceramic tile	0.0038	–	–	–	–
Plaster	0.25E-03	–	–	–	–
Wood	0.56E-04	0.15	0.55	0.56	0.56
Paper	0.65E-06	0.01	0.05	0.05	0.05
Organics	0.0024	8	30.5	30.84	30.84
Total	0.18	8.16	31.1	31.4	31.4

Table 11
N_2O emission calculation results.

NO.	Material type	Transportation emissions (tonne)
1	Soil	0.0025
2	Concrete	0.013
3	Brick	0.003
4	Cement	0.002
5	Lime	0.055
6	Mortar	0.24E-05
7	Steel	0.79E-03
8	Ceramic tile	0.56E-03
9	Paint	0.15E-06
10	Polymer coating	0.9E-05
11	Plastic	0.11E-04
12	Wood	0.83E-05
13	Paper	0.96E-07
14	Asphalt	0.34E-03
15	Plaster	0.37E-04
Total		0.077

(4) **Asphalt had the highest CO_2 emission capacity.** From Fig. 6, it can be seen that while asphalt only accounted for 1.28% of total CDW, the lowest of the large quantity CDW, it emitted the second largest total CO_2 emissions at 2902.7 tonnes or 24.89% of the total. Therefore, although the asphalt quantities were the smallest, it had high CO_2 emission capacity. Of total emissions, the asphalt recycling emissions only accounted for 2.56% of the total recycling emissions; however, the asphalt landfill emissions accounted for 28.49% of the total landfill emissions. *5.4.1.2.* CH_4 *emissions*

Table 13
CDW quantity and CH_4 decomposition emission percentages.

NO.	Material type	Quantities (%)	Emissions			
			1 year (%)	20 years (%)	50 years (%)	100 years (%)
12	Wood	2.26	1.84	1.77	1.78	1.78
13	Paper	0.03	0.12	0.16	0.16	0.16
–	Organics	97.72	98.04	98.07	98.06	98.06

The CH_4 decomposition emission distributions are shown in Fig. 7, and the CDW quantity and CH_4 decomposition emission percentages are shown in Table 13.

(1) **The CH_4 emissions varied over time.** First, from the landfill years shown in Fig. 7, as the CDW landfill years increased, the CH_4 emissions also grew, with the largest increase being experienced in the 1–20 year range. However, when the CDW landfill time reached a certain level, for example 100 years, the CDW methane emissions were stable.

(2) **Organics had the highest CH_4 emissions.** The organics, 97.72% of the quantities for which were composed of four CDW types, accounted for 98.04% of the CH_4. As can be seen,

Table 12
CDW quantity and CO_2 handling emission percentages.

NO.	Material type	Amounts (%)	Recycling emissions (%)	Landfill emissions (%)	Total emissions (%)
1	Soil	9.29	2.54	1.8	1.9
2	Concrete	47.14	78.73	59.4	62.09
3	Brick	11.19	1.49	3.25	3.01
4	Cement	7.57	1.01	1.47	1.4
5	Lime	0.00912	0.0012	0.0018	0.0017
6	Mortar	18.18	2.43	3.52	3.37
7	Steel	2.98	10.55	0.87	2.21
8	Ceramic tile	2.12	0.35	0.37	0.37
9	Paint	0.0006	0.0012	0.0125	0.011
10	Polymer coating	0.0338	0.068	0.75	0.65
11	Plastic	0.0418	0.093	0.008	0.02
12	Wood	0.0313	0.11	0.015	0.03
13	Paper	0.00036	0.004	0.008	0.0073
14	Asphalt	1.28	2.56	28.49	24.89
15	Plaster	0.138	0.05	0.027	0.03

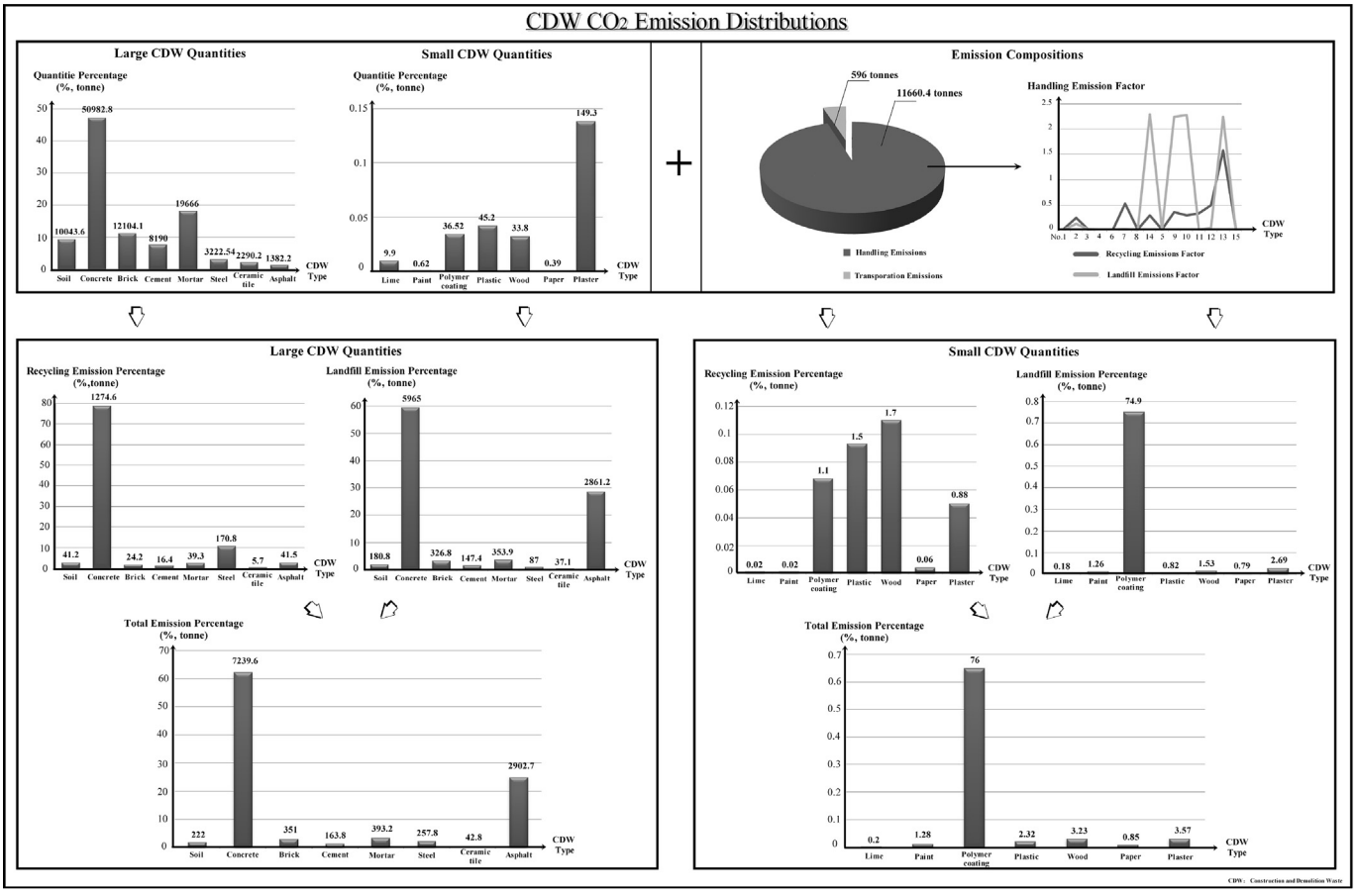

Fig. 6. : CO_2 handling emission distributions.

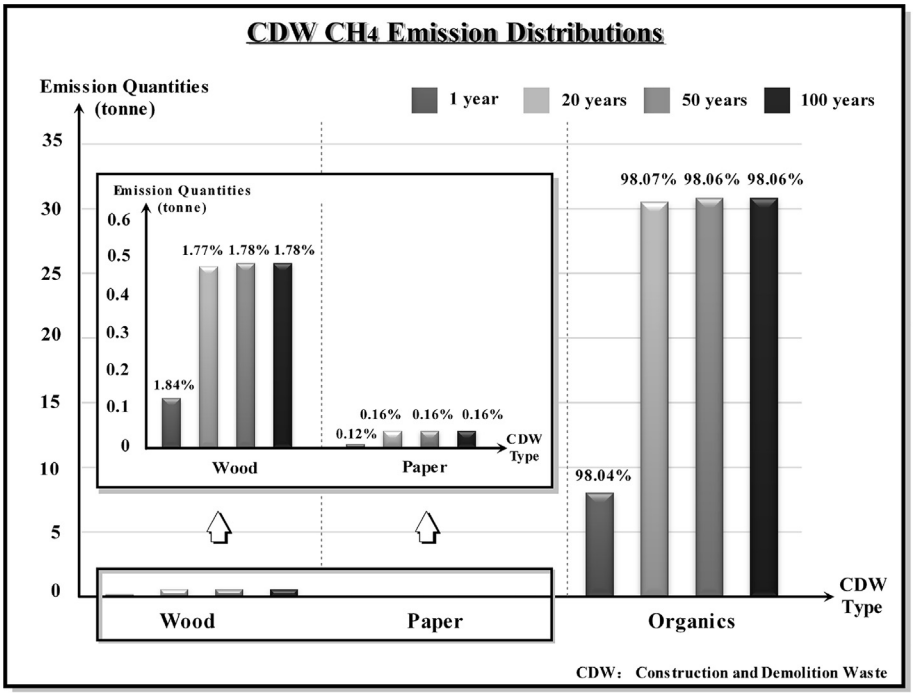

Fig. 7. : CH_4 decomposition emission distributions.

over time, the CH_4 emissions increase, with the CH_4 emissions of organics always being the highest. Therefore, the most significant waste contributor were the organics, which also had the highest methane emissions.

(3) **Paper had high CH_4 emission capacity.** From Table 4 and Table 13, it can be seen that there were 0.39 tonnes of paper, which accounted for 0.03% of the CDW; however, it emitted 0.12%–0.16% of CH_4. Therefore, although the amount of CH_4 emitted from paper is not very large, the CDW paper capacity to emit methane is strong compared to its CDW quantities.

From the case application above, it can be seen that the BIM models were successfully established, from which detailed information about 15 elements was obtained. After conversions, information for each CDW type was accurately obtained, which indicated that the BIM-based CDW IMS proposed in this paper was fully applied. Then, combining the obtained CDW information with mathematical formulae, detailed GHG emissions from the 15 CDW types were determined respectively, including transportation and handling CO_2 emissions, transportation and decomposition CH_4 emissions and transportation N_2O emissions. Therefore, it can be obtained that the CDW GHG emission problems were successfully and sufficiently solved through the methodology proposed in this paper. And after the successful application of the case, some practical suggestions can be given.

5.4.2. Suggestions

Based on the analyses above, targeted GHG emission reduction measures are developed for each CDW to reduce the environmental impact and go some way towards sustainable CDW disposal (Saieg et al., 2017).

(1) **To ensure greater environmental protection, more attention needs to be paid to handling and decomposition emissions.** In cities with shorter transportation distances, the CDW disposal transportation emissions and especially the CH_4 and N_2O transportation emissions would be smaller than the handling emissions. Although CH_4 and N_2O can seriously damage the environment, the transportation emission volumes were only respectively 0.18 and 0.077 tonnes in this paper. Therefore, management needs to pay greater attention to handling and decomposition emissions to reduce air pollution and achieve sustainable development.

(2) **To reduce the CO_2 handling and CH_4 decomposition emissions and to better target management, it is suggested that, the CDW be divided into three categories.** That is, CDW with large GHG emissions, large quantity CDW, and CDW with small GHG emissions. For these three categories, different types of CDW management and targeted GHG emission reduction measures can be given, which are highly effective and valid.

(3) **CDW recycling and landfill rates for large CO_2 emission capacity CDW should be adjusted.** That is, when the CDW has large recycling emissions, the landfill rate could be increased and the recycling rate reduced; however, when the CDW recycling emissions are small, the landfill rate should be reduced and the recycling rate increased. For example, as both asphalt and polymer have high CO_2 emissions and the landfill emission percentage are far greater than the recycling emission, to reduce the CO_2 emissions, the recycling rate for these types of CDW could be increased and the landfill rate decreased.

(4) **For CDW that has large CH_4 emission capacity, the CDW recycling rate and landfill years should be controlled.** The high CH_4 decomposition emissions can be adjusted by increasing the recycling rate and reducing the landfill years. For example, as paper emits high CH_4, increasing the recycling rate or reducing the landfill time could reduce the associated CH_4 emissions.

(5) **Improving waste performance, increasing recycling, or reducing materials use could be considered for large quantity CDW.** For example, as concrete CDW quantities are generally very high in the construction industry, there are commensurately high recycling and landfill emissions, which means that increasing the recycling or landfill rates would not significantly reduce the GHG emissions. Therefore, the best way to reduce these types of CDW environmental pollution would be to improve performance. In another example, as organics are the main source of CH_4 emissions, paying attention to reducing the quantity of organics being used in the construction process could also assist in reducing GHG emissions.

(6) **The disposal of low emitting CDW could be considered from other perspectives.** As CDW that has small GHG emissions could have small harm to the environment, managing these from other perspectives could be meaningful. For example, in this paper, although the quantities of mortar, brick, soil, etc. were large, the associated GHG emissions and environmental pollution were small. Therefore, the disposal of these types of CDW could be based on cost without worrying about the environmental impact.

6. Conclusions

GHG emissions have already had a serious effect on the environment, much of which can be attributed to the significant increase in CDW from increased urbanization and industrialization activities. Therefore, precise CDW information estimation and accurate CDW disposal GHG emission quantification are vital to ensure targeted reduction measures to be developed. This paper proposed an effective new methodology that combined a BIM-based CDW IMS and mathematical formulae to ensure accurate CDW information and GHG emission quantification. A BIM-based CDW IMS was first established, for which detailed and precise information regarding source-separated CDW was obtained. Mathematical formulae were then employed to calculate the GHG emission quantities for each type of CDW disposal. Finally, the proposed methodology was applied to a real case study, in which the detailed GHG emission situations for 15 types of CDW were obtained. Emission comparisons and analyses were then conducted and targeted GHG emission reduction measures and CDW management suggestions were given for the different CDW types.

The proposed CDW IMS obtained precise CDW information and accurately quantified the associated GHG emissions for source-separated CDW disposal. Concrete waste was found to have the highest CO_2, CH_4, and N_2O transportation emissions, and the highest CO_2 handling emissions at 62.09% of total handling emissions. Organics were found to have the highest CH_4 decomposition emissions at 97.72% of total decomposition emissions. To reduce the CDW disposal GHG emissions, the CDW was divided into three categories and six targeted suggestions were given based on the different CDW characteristics. With precise CDW disposal GHG emission quantification and targeted management suggestions, the environmental damage caused by CDW disposal GHG emissions could be controlled and reduced.

The main contributions of this paper are as follows: (1) As CDW disposal GHG emissions have not been fully considered in the past, this paper focuses on the quantification of and reduction in CDW disposal all related GHG emissions to reduce environmental damage. (2) The BIM-based CDW IMS developed in this paper gives

information directly about CDW and describes how the CDW information is obtained from the BIM; (3) the innovative combination of BIM technology and mathematical formulae allows for feasible and precise CDW disposal GHG emission quantification, which can assist decision makers make targeted plans to reduce source-separated CDW GHG emissions based on regional needs.

However, there are also avenues for future research: (1) Although this paper combined a software system and mathematical formulae, these two elements were still separate; that is, the information and CDW data obtained from the software system needed to be manually arranged and then manually input into the algorithmic programs to obtain the CDW GHG emissions. Therefore, future research could consider integrating these elements to make the approach easier to use. (2) As this paper only considered CDW end of life management GHG emissions, for a more comprehensive analysis, future studies could consider adding in the GHG emission quantification after CDW remanufacturing to compare GHG reduction emissions bring by CDW recycle with new material production. (3) This paper proposed CDW disposal methods from an environmental protection perspective. However, as handling some CDW does not threaten the environment, other handling decisions such as economic benefits could be considered. Therefore, future studies could add CDW economic benefits analyses and a trade-off assessment between the environment and the economy.

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